Investigation of Glacier Dynamics During the Last Glacial Maximum at Tioga Pass, Yosemite National Park

by
Alexander Gage Laub

A THESIS

submitted to

Oregon State University

Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Earth Sciences
(Honors Associate)

Presented August 30, 2021
Commencement June 2022

AN ABSTRACT OF THE THESIS OF

Alexander Gage Laub for the degree of Honors Baccalaureate of Science in Earth Sciences presented on August 30, 2021. Title: Investigation of Glacier Dynamics During the Last Glacial Maximum at Tioga Pass, Yosemite National Park.

Abstract approved:____

Peter Clark

Previous investigations of glacier dynamics at Tioga Pass during the Last Glacial Maximum (LGM) have produced different conclusions. A map of the LGM ice extent and flow direction (Alpha et al., 1987) illustrates a south-to-north direction of ice flow across the pass with little evidence to support this inference. Since the production of this map, unexpected glacial erratics of Cathedral Peak Granodiorite (CPG) have been noted in the vicinity of Tioga Pass, which are not consistent with the inferred flow direction. A comprehensive spatial data set of CPG erratics was collected. This data was collected between Tioga Lake and the southeastern boundary of the CPG bedrock, south of Tioga Pass. The erratics display trends of decreasing abundance from north to south, characteristic of boulder trains used to infer glacier flow patterns. Based on these trends, the erratics indicate a north-to-south flow across the pass, opposite to what Alpha et al. (1987) had inferred. This flow is determined to have originated from the eastern cirque of Mt. Conness, the northeastern boundary of the CPG bedrock. The Excel spreadsheet, "Profiler V. 2" (Benn and Hulton, 2009) was used to model the flows from Mt. Conness down the Lee Vining Canyon and the Grand Canyon of the Tuolumne River; these flows branched at Tioga Lake. The model provided insight into the ice dynamics in this region but was unable to provide insight into small flow reversals. Based on the distribution of CPG erratics, the "Profiler V. 2" analysis, past field research yielding evidence of other erratic boulder trains, a comprehensive set of striations and glacial landforms, and a plan-view map of ice coverage and flow direction at the peak of the LGM (Wahrhaftig et al., 2019), there is evidence to support the standing hypothesis that ice flowed south across Tioga Pass at the peak of the LGM, then became stagnant, with ice from Mt. Conness and Tioga pass eventually flowing into Lee Vining Canyon after peak LGM conditions receded.

Key Words: Yosemite, Last Glacial Maximum, glacier, glacier dynamics, Tioga Pass, Cathedral Peak Granite, Profiler V.2

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APPROVED:

Peter Clark, Mentor, representing College of Earth, Ocean, and Atmospheric Sciences

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Kaplan Yalcin, Committee Member, representing College of Earth, Ocean, and Atmospheric Sciences

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Greg Stock, Committee Member, representing National Park Service

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Toni Doolen, Dean, Oregon State University Honors College

I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

Alexander Gage Laub, Author

INVESTIGATION OF GLACIER DYNAMICS DURING THE LAST GLACIAL MAXIMUM AT TIOGA PASS, YOSEMITE NATIONAL PARK

ABSTRACT

Previous investigations of glacier dynamics at Tioga Pass during the Last Glacial Maximum (LGM) have produced different conclusions. A map of the LGM ice extent and flow direction (Alpha et al., 1987) illustrates a south-to-north direction of ice flow across the pass with little evidence to support this inference. Since the production of this map, unexpected glacial erratics of Cathedral Peak Granodiorite (CPG) have been noted in the vicinity of Tioga Pass, which are not consistent with the inferred flow direction. A comprehensive spatial data set of CPG erratics was collected. This data was collected between Tioga Lake and the southeastern boundary of the CPG bedrock, south of Tioga Pass. The erratics display trends of decreasing abundance from north to south, characteristic of boulder trains used to infer glacier flow patterns. Based on these trends, the erratics indicate a north-to-south flow across the pass, opposite to what Alpha et al. (1987) had inferred. This flow is determined to have originated from the eastern cirque of Mt. Conness, the northeastern boundary of the CPG bedrock. The Excel spreadsheet, "Profiler V. 2" (Benn and Hulton, 2009) was used to model the flows from Mt. Conness down the Lee Vining Canyon and the Grand Canyon of the Tuolumne River; these flows branched at Tioga Lake. The model provided insight into the ice dynamics in this region but was unable to provide insight into small flow reversals. Based on the distribution of CPG erratics, the "Profiler V. 2" analysis, past field research yielding evidence of other erratic boulder trains, a comprehensive set of striations and glacial landforms, and a plan-view map of ice coverage and flow direction at the peak of the LGM (Wahrhaftig et al., 2019), there is evidence to support the standing hypothesis that ice flowed south across Tioga Pass at the peak of the LGM, then became stagnant, with ice from Mt. Conness and Tioga pass eventually flowing into Lee Vining Canyon after peak LGM conditions receded.

INTRODUCTION

Yosemite National Park, a crown jewel of the Sierra Nevada in California, is home to a rich history of glaciation. Tioga Pass, the eastern entrance into Yosemite, is among the most well-known mountain passes in the United States. It is characterized by deep "U" shaped valleys, sweeping headwalls, large erratic boulders, hummocky topography, and dramatic mountain peaks. While all these characteristics are evidence for extensive glaciation, the dominant ice dynamics which shaped its inspiring topography have remained uncertain.

Throughout the Quaternary Period, the full Sierra Nevada mountain range experienced extensive ice coverage. The glacial cycles were characterized by coalescent icefields that spilled ice tongues into the Owens Valley to the east, to the fringes of the San Joaquin Valley to the west, and periods of isolated glaciers confined to their cirques (Matthes, 1929; Blackwelder 1931). While each of these glacial cycles were responsible for unique erosional and depositional patterns, much of the evidence is erased or buried by any subsequent ice advance. The record of each event is often only recorded by the depositional sequence of terminal moraines best preserved off the eastern slopes of the mountain range. Various field mapping and radiometric dating efforts are responsible for identifying at least seven unique glacial periods, with four major periods of advance (Blackwelder, 1931; Sharp and Birman 1963; Wood, 1977; Fullerton, 1986; Phillips et al., 1990; Phillips et al., 1996; Gillespie and Clark, 2011).

The most recent period of extensive icefield coverage in the Sierra Nevada occurred during the globally recognized Last Glacial Maximum (LGM, ~26.5 ka to ~19 ka) (Clark et al., 2009). In the Sierra Nevada, the icefields reached their maximum extent at approximately 21 ka and remained until approximately 18 ka. This period is known locally as the Tioga glaciation (~31 ka to ~15 ka) (Bursik and Gillespie, 1993; Phillips et al., 1996; Clark et al., 2003; Phillips et al., 2009; Gillespie and Clark, 2011) and is responsible for much of the remaining Pleistocene sedimentological and geomorphic record in Yosemite. The maximum extent of ice coverage in Yosemite National Park during the Tioga glaciation was mapped with the assumption that ice reached its maximum extent at all locations simultaneously (Alpha et al., 1987). This work was later revised and enhanced (Wahrhaftig et al., 2019).

This recent mapping endeavor spearheaded by Greg Stock, the Yosemite National Park Geologist, built on years of work left unfinished by Clyde Wahrhaftig, an avid naturalist and geologist. It identified multiple ice-flow directions in regions surrounding Tioga Pass. Glacial striations suggest that the dominant ice-flow direction near Tioga Pass was to the northeast, down Lee Vining Canyon. In contrast, glacial erratics have been noted along the pass (erratum to Alpha et al., 1987) and further south in the Dana Fork drainage (Huber, 2001), which indicate an ice flow direction southward across Tioga Pass, a contradiction to the flow direction inferred from nearly all the mapped striations. The erratics are largely comprised of Cathedral Peak Granite (CPG), a distinctive granitic rock characterized by potassium feldspar megacrysts, an easily distinguishable feature. Given the distribution of the CPG bedrock in Yosemite's high country and the widely agreed upon westerly flow of ice from southwest of the Tioga Pass, it has been inferred that the CPG erratics present at the pass are likely to have been plucked and transported from the CPG bedrock outcroppings northwest of Tioga Pass, notably from the eastern cirque walls of Mt. Conness. This would imply a southeastern ice flow direction up to the pass, with a southern direction of flow over the pass, in contrast to the direction suggested by the striations.

The prevailing hypothesis proposes that during the maximum extent of glaciation during the LGM, the ice flowed south across the pass, and as it began to thin, it deposited the CPG erratics. As the flow down Lee Vining Canyon also retreated, it is possible that this caused the ice to thin enough to induce a reversal in the flow direction across Tioga Pass, leading to northeasterly flow down Lee Vining Canyon. This could have overprinted many of the striations that pointed toward southward ice flow and formed the northeast trending striations. This hypothesis emphasizes the inherent risk in using striations as evidence for dominant ice flow direction, given that subsequent changes in flow direction may erase previous indicators (Wahrhaftig et al., 2019).

Early studies suggested flow from Kuna Crest to the Mono Lake drainage basin via a northeasterly flow across Tioga Pass (Alpha et al., 1987). This explanation seems to be based on current topography, however, the icefields covering the crest of the Sierra Nevada may not have been fully constrained by topography. More recently, a mapped boulder train of metamorphic rocks originating largely east of Tioga Pass illustrates that the ice flow from Kuna Crest was diverted west before Tioga Pass (Wahrhaftig et al., 2019), thus disagreeing with the original hypothesis by Alpha et al. (1987) for ice flow over the pass. Huber (2001) also noted the presence of boulders at the pass, this time noting more CPG boulders further south, yet these observations have yet to result in the reevaluation of maps or focused explanations of the Tioga Pass ice flow.

This thesis consists of mapping the distribution of CPG erratics between Tioga Lake and Tuolumne Meadows to provide a clearer understanding of the direction of ice flow around Tioga Pass at the maximum extent of glaciation. This work will attempt to use various components of new and past field evidence, along with ice-surface level projections at the maximum extent of glaciation to infer how ice retreat and thinning may have altered flow directions. This thesis uses field mapping, spatial analysis, and glacier modeling to evaluate ice-flow history.

The aim of this thesis is to synthesize the work done thus far on ice flow directions around Tioga Pass during the LGM, create a new dataset of all CPG erratics present around Tioga Pass, and explain the contradictory evidence for various ice flow directions.

Figure 1 – A plan-view map of ice coverage and flow direction at the peak of the LGM (Wahrhaftig et al., 2019).

PREVIOUS WORK

While many have contributed to the present body of knowledge regarding the processes responsible for the dramatic landscape of Yosemite, this work is so vast that a focused synopsis directly related to mapping of the maximum extent of Tioga-age glaciation is in order.

The glacial geology of Yosemite was first studied in 1863 when three members of the Geological Survey of California–Josiah D. Whitney, William H. Brewer, and Charles F. Hoffmann–visited the high alpine region of Tuolumne meadows. Their observations and notes were the first to identify glacial features, notably moraines which were indicative of the glacial history (Whitney, 1865).

These insights opened the doors for further inquiry. From the 1860s through the 1930s naturalists and geologists, such as Clarence King, John Muir, Israel Russel, François Matthes, and Elliot Blackwelder, played pivotal roles in developing a knowledge base of glaciation in Yosemite and the greater Sierra Nevada. Their studies helped bring to light the multiple periods of glaciation which shaped the Sierra Nevada topography, but the scale of these glaciations had yet to be fully grasped.

While these individuals laid the framework for investigating the glacial history of Yosemite, none truly helped the untrained eye comprehend the scale and flow of glacial icefields during the most recent glacial maximum (Tioga glaciation) quite like Clyde Wahrhaftig, his peers, and those who carried out his vision after his passing. Wahrhaftig, a field geology professor for UC Berkeley and a USGS geologist, was granted funding by the USGS in the early 1980s to carry out a detailed investigation of the maximum Tioga-age glaciation extent. With the help of Malcom Clark and N. King Huber, Wahrhaftig compiled a wealth of field evidence pertaining to the Tioga-age maximum glaciation extent (Wahrhaftig et al., 2019). In 1987, Tau Rho Alpha, Clyde Wahrhaftig, and N. King Huber constructed, by hand, the first map to illustrate the volume and movement of ice across Yosemite's landscape at the peak of the Tioga glaciation (Alpha et al., 1987).

The publication of this map was accompanied by an erratum, highlighting field evidence used to discredit the flow lines immediately west of the Mt. Dana. These branching lines suggested flow from Mt. Dana, Mt. Gibbs, and Kuna Crest branching into one flow heading west toward Tuolumne Meadows and another headed north across Tioga Pass and into Lee Vining Canyon. The erratum pointed specifically to a boulder train of metamorphic boulders originating from the western slopes of Mt. Dana and mapped extensively in the direction of Tuolumne Meadows. This indicated ice flow from the western slopes of Mt. Dana into Tuolumne Meadows, meaning no ice could have flowed north past this ice stream (*figure 2,* B). This erratum was also the first mention of CPG boulders at Tioga Pass, and the first instance of a proposed southward flow of ice across Tioga Pass with Mt. Conness as the proposed origin.

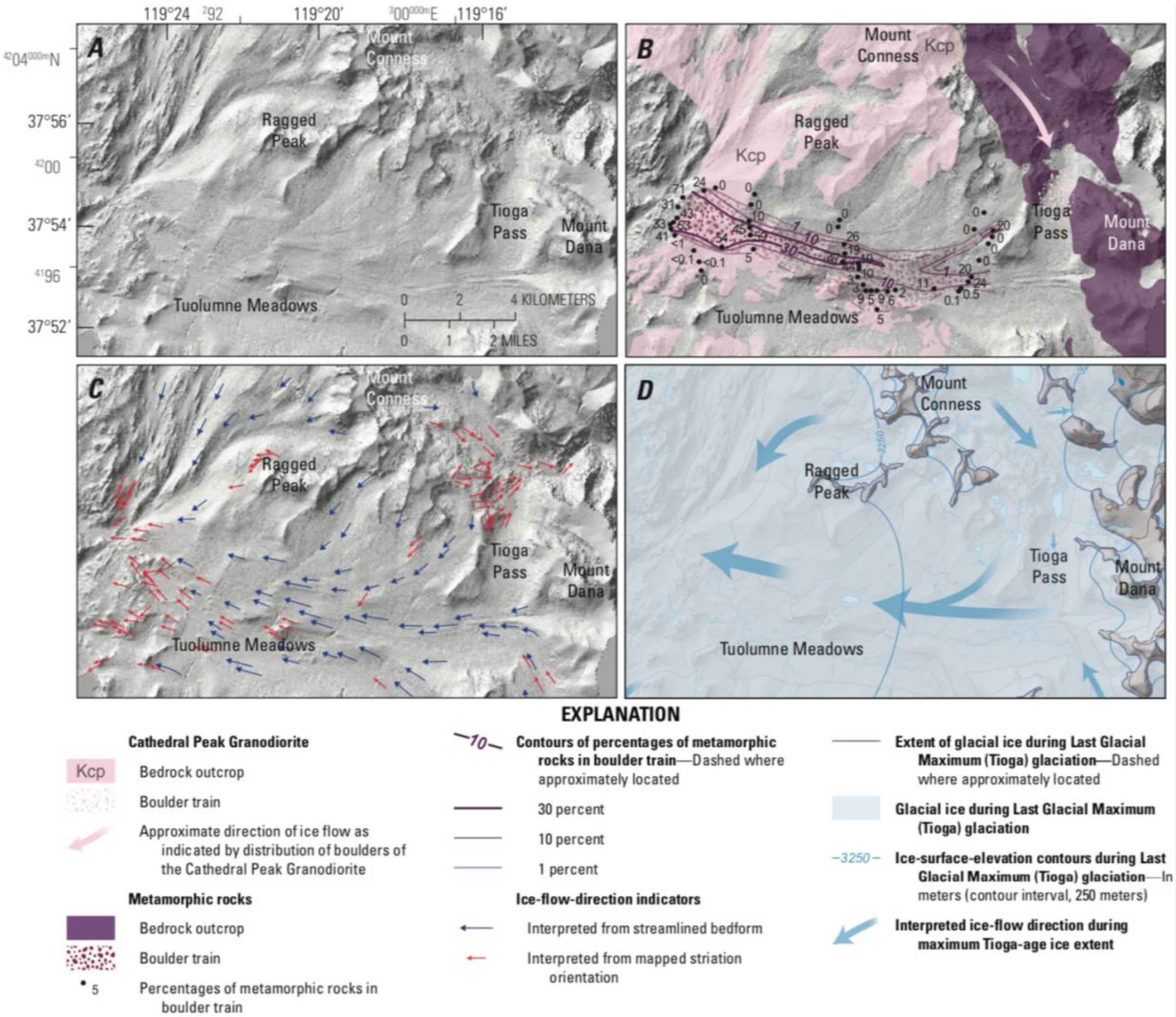

Figure 2 - Shaded-relief maps of area around Tuolumne Meadows and Tioga Pass in Yosemite National Park, showing ice-flow directions determined from field and remote-sensing mapping. Shaded-relief base map derived from 1-m-resolution filtered airborne-lidar data. A*, Map showing streamlined bedforms such as crag-and-tails and moraines.* B*, Same area as* A*, showing distribution of distinctive bedrock lithologies, as well as of glacial deposits composed of those lithologies, which reveal ice-flow directions. Erratics (boulders)of the Cathedral Peak Granodiorite at Tioga Pass originated from bedrock exposures near Mt. Conness and were transported by ice flowing southward toward Tioga Pass (Huber, 2007). Large, persistent boulder train of metamorphic rocks north of Tuolumne Meadows was transported by ice flowing westward from metamorphic rocks near Mt. Dana. Bedrock geology simplified from Huber and others (1989).* C*, Same area as* A*, showing mapped glacial striations and streamlined bedforms that indicate directions of basal ice flow. Striations near Tioga Pass indicate that ice flowed northeastward, away from Tioga Pass, opposite to flow direction inferred from boulders of the Cathedral Peak Granodiorite shown in* B*. These apparently conflicting lines of evidence can be reconciled using scenario in which ice flowed southward across Tioga Pass during time of maximum ice extent and then subsequently reversed course as glaciers receded.* D*, Same area as* A*, with overlay that shows ice extent and ice-flow directions during time of maximum ice extent.*

In 2001, N. King Huber wrote an excerpt in the spring edition of the Yosemite journal in which he further discredited his decision to indicate a northward flow line across Tioga Pass. This time Huber pointed primarily to the distribution of CPG boulders found around Tioga Pass, of which he noted a high concentration near the peak of the pass, and boulders as far south as the

Dana Fork, approximately a mile from the eastern CPG bedrock boundary. Further, Huber noted a decrease in abundance of the CPG erratics with increasing distance south of Tioga Pass and inferred a southward ice flow across Tioga Pass that would have been compressed and directed westward by the westward flow from the western slopes of Mt. Dana and the north-westward flow from the Kuna Crest region (Huber, 2001).

Wahrhaftig intended to release a plan-view version of the map, adding more detail and correcting errors from the 1987 edition, but deteriorating health forced him to pass the project on to future researchers. With the help of Wahrhaftig's trust funds granted to Greg Stock, work began to complete Wahrhaftig's vision. With the help of Reba G. McCracken, Peri Sasnett, and Andrew J. Cyr, Stock completed this plan-view map twenty-five years after Wahrhaftig's passing (*figure 1*). The map includes another decade of research, but like Wahrhaftig, the researchers noted that such a large body of work will certainly never be perfect. In 2019, prior to the publication of the plan-view map, Stock requested a detailed investigation of the CPG erratics found around Tioga Pass with the intention of conducting a more in-depth evaluation of the ice dynamics at the peak of the Tioga-age glaciation. Stock's request set the foundation for the research presented in this thesis.

METHODS

The data for this thesis consists of a combination of past field evidence collected largely by Clyde Wahrhaftig and Greg Stock, as well as a new comprehensive data set noting the position of all CPG erratics found between Tioga Lake and Tuolumne Meadows. This thesis ultimately uses these spatial datasets along with glacial landforms observed using Lidar imagery, and the "Profiler V.2," Excel™-based spreadsheet for modelling glacier profiles to pinpoint the dominant ice flow direction across Tioga Pass at the peak of the LGM and infer any potential shifts in this flow direction following peak glaciation.

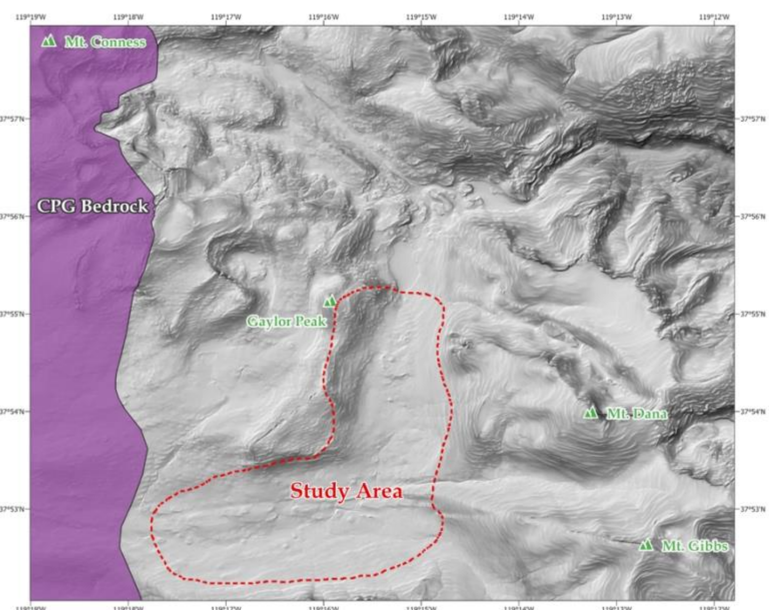

Figure 3 – This map depicts the study area for this project and all regions of importance. The study area consists of Tioga Pass Valley (north of "Study Area") and the Dana Fork drainage (south and west of "Study Area"). The study area is the area scanned for CPG erratics. Lee Vining Canyon runs east to west, and is found just north of the study area, running to the eastern edge of the map. The crest of Tioga Pass sits at an elevation of 3031 meters.

FIELD MAPPING

The comprehensive spatial dataset of all CPG erratics around Tioga Pass was created by on-the-ground field mapping. The position of each unique erratic was recorded using a Garmin InReach GPS over the course of 10 days.

During the early stages of investigation, boulders were found by repeated east-to-west sweeps from Tioga Lake to the crest of Tioga Pass.

Middle stages of field mapping consisted of establishing a perimeter for the field data, after initial inquiries proved the distribution of erratics to be extensive. This perimeter reached as far north as Tioga Lake (based on statements from Stock that boulders were prolific in Lee Vining Canyon) and extending to roughly 3110 meters on the east and west side of the glacial valley.

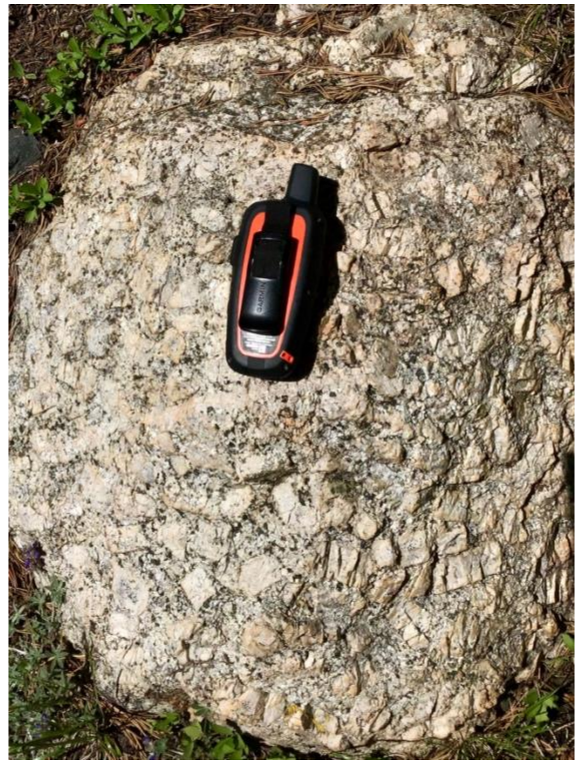

Figure 4 - CPG erratic found at Tioga Pass. Note the characteristic potassium feldspar phenocrysts (Garmin InReach used for scale).

The final stages of field mapping consisted of east-to-west sweeps across the valley meadows south of the Tioga Pass crest, thorough sweeps through dense forest (where terrain permitted), and re-evaluation of small sections missed in previous days. Field mapping concluded with an exhaustive search for CPG erratics in lateral moraines and hummocky topography downstream from the last noted CPG erratics found in the Dana Fork drainage.

While this field mapping was thorough and far-reaching, it became increasingly clear that with a data set so large and a study area so vast, there are almost certainly a handful of CPG erratics whose positions were not recorded. As a byproduct of the scrutiny used in this research, it is unlikely that any large groupings of CPG erratics were missed which would notably affect the density distribution, or any observable trends. Any omission of CPG erratics within the main study area is likely negligible, and any omissions near the fringes of the study area are unlikely to alter any inferences or conclusions.

USE OF PREVIOUS WORK

This project relies heavily on the wealth information collected by Clyde Wahrhaftig, Greg Stock and all the accompanying researchers. Three data sets are pivotal to analyzing the evolution of ice dynamics around Tioga Pass:

(1) a comprehensive list of striations (bedrock abrasions caused by entrained debris at the base of the glacier) in and around Yosemite National Park (a subset of these striations are depicted in *figure 2,* C) (Wahrhaftig et al., 2019);
(2) a map of a metamorphic boulder train in the Dana Fork drainage south of Tioga Pass (*figure 2,* B) (Huber, 2007);
(3) a plan-view map of ice coverage and inferred flow directions created by Greg Stock (*figure 1*) (Wahrhaftig et al., 2019).

While none of these pieces can singlehandedly tell the story of the evolving ice dynamics around Tioga Pass, their combination along with the other data amassed in this project helps make important inferences.

GLACIAL LANDFORMS

Two types of glacial landforms are useful to understanding ice dynamics around Tioga pass:
(1) streamlined bedforms (namely roche moutonnées);
(2) glacial valleys.

The first of the two refers to bedrock outcrops characterized by "stoss and lee" sides, indicative of ice flow over the smooth (stoss) side and past the steep (lee) side (see, for example, Benn and Evans, 2013; Munro-Stasiuk and others, 2013). Well preserved features often indicate the most recent dominant direction of ice flow since glaciers abrade the up-ice side and quarry the down-ice side of the roche moutonnée landforms. Pressure builds up on the up-ice side of the landform, and low-pressure zones develop down-ice from the outcrop, increasing stress on pre-existing cracks in the outcrop. This causes chunks to break loose where they either become frozen onto the glacier or are dragged along by the basal ice.

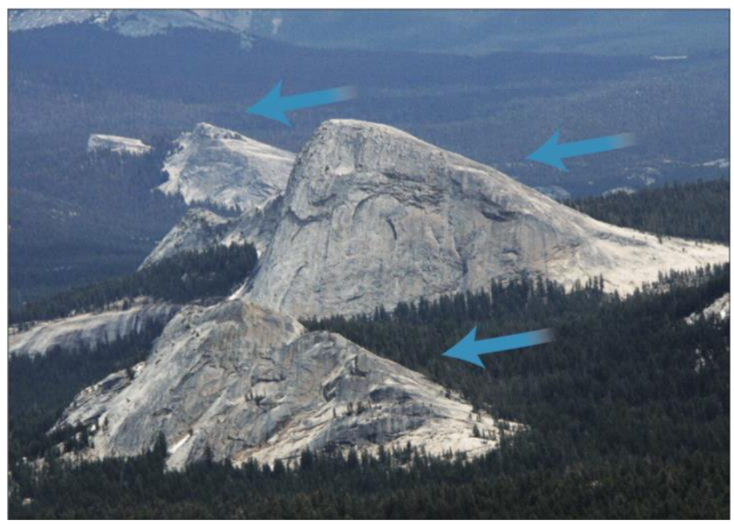
Figure 5 - Roche moutonnées from Tuolumne Meadows just west of the study area. Similar features can be found north of Tioga Lake. Image courtesy of Greg Stock (Wahrhaftig et al., 2019).

At first glance, glacial valleys may seem like rudimentary features providing no additional information. However, in the case of the Sierra Nevada icefields, there was often no single point from which each ice flow diverged. Often, unique flows would converge, potentially altering the structure and flow direction of the ice (Bons et al., 2016).

PROFILER V.2

The “Profiler V.2” is an Excel™-based spreadsheet designed to calculate the ice surface profile of past glaciers based on a “perfectly plastic” glacier model (Benn and Hulton, 2009). Such a model assumes that irrecoverable strain takes place when the specific yield stress and the basal shear stress are equal. The spreadsheet is designed to take four inputs:

(1) a bed profile with a step increment along the x-axis and corresponding elevations along the y-axis;
(2) target elevations (based on lateral moraines, trimlines, or other field evidence);
(3) shear stress;
(4) a shape factor (a parameter which accounts for any side-drag a glacier experiences because of contact with the confining valley).

In return, the spreadsheet is configured to output an ice surface elevation and an ice thickness. The spreadsheet also uses earth’s gravity (9.81 m/s^2) and density of ice (900 kg/m^3) as constant parameters.

For this project, two flows were modeled (appendix 1):

(1) Mt. Conness to Lee Vining Canyon;
(2) Mt. Conness to Grand Canyon of Tuolumne.

The bed profiles for each flow were analyzed using Google Earth Pro™, the target elevations were assigned based on ice surface contour lines from Greg Stock’s plan-view map of ice coverage in and around Yosemite at the peak of the LGM (*figure 1*), the shear stress was adjusted to match calculated ice surface to the target elevations, and shape factors were calculated at major changes in the confining valley width using the built in shape factor calculations and cross sections of the bed profiles using Google Earth Pro™ (this requires a cross section, comprised of horizontal and vertical distances). By modelling these two flows the goal is to better understand the ice dynamics around Tioga pass. This model will also produce continuous surface elevation profiles for each glacier. Given that ice flow is heavily governed by ice surface slope, neighboring regions of the flows can also be compared to evaluate flow direction.

DISCUSSION OF RESULTS

DISTRIBUTION OF CPG ERRATICS

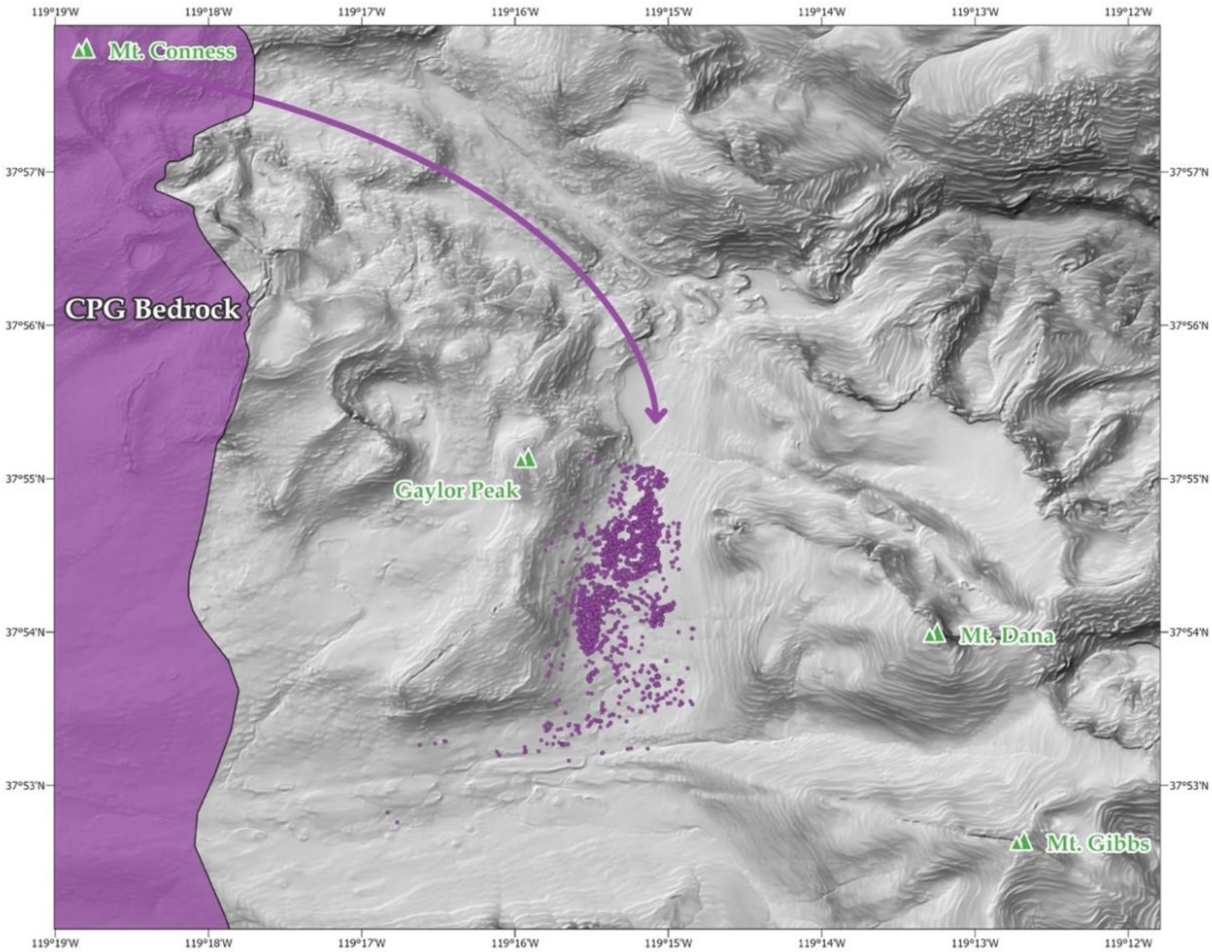

Figure 6 – The distribution of all recorded CPG erratics south of Tioga Lake. The purple line indicates the flow responsible for depositing the CPG erratics, and the purple points indicate the 2622 individual CPG erratics.

A total of 2622 CPG glacial erratics were recorded between Tioga Lake and Tuolumne Meadows, with 1952 of those observations located south of the crest of the pass. The distribution clearly shows the highest concentrations of CPG erratics within a few hundred meters of the pass crest, with some other dense sections further south, within approximately 1000 meters of the pass crest. The density distribution begins to taper off after this point, exhibiting a gradual decrease in density until roughly 3000 meters from the pass crest. Nearly all these CPG erratics were found north of the Dana Fork of the Tuolumne River, specifically, they were highly concentrated north and west of all glacial cirques and valleys on the southern end of Mt. Dana. Patches of lower density coincide with the confluence of Mt. Dana's southwestern glacial cirques and valleys, and the study area valley (to be referred to hence forth as Tioga Pass Valley). A small set of CPG erratics was found to the southwest of Tioga Pass Valley, where they valley is no longer confined between the western ridge (south of Gaylor Peak) and the eastern valley walls (Mt.

Dana's western slopes). Of this small set, three CPG erratics were observed around approximately 3800 meters from the pass crest. All three of these CPG erratics were found near the base of lateral moraines comprised primarily of Kuna Crest Diorite.

This field evidence not only confirms the presence of CPG erratics around Tioga Pass, but also established CPG erratics as a primary lithology of all erratics within Tioga Pass Valley. Based on streamlined bedforms running east-to-west off the southern slopes of Mt. Dana, and Wahrhaftig's map of the metamorphic rocks transported from Mt. Dana into Tuolumne Meadows, there is strong evidence that ice flowing off the southwestern slopes of Mt. Dana diverted any flows from Kuna Crest (south of Mt. Dana) to the west into Tuolumne Meadows, away from Tioga Pass Valley. Further, visual analysis of the CPG erratic density distribution shows a clear decrease in density with greater distance south of Tioga Pass. Based on this evidence, the conclusion that the CPG erratics around Tioga were transported from Mt. Conness (Wahrhaftig et al., 2019) is strongly supported.

In addition to this, specific trends observed within the overall distribution of CPG erratics may provide insight into the ice dynamics in this region. Of note are two observations:

(1) the abrupt decrease in CPG erratic abundance in the southern portion of Tioga Pass Valley;
(2) the stratigraphic positioning of the three observed CPG erratics most distant from the pass crest.

This first observation aligns with small glacial cirques and larger valleys originating on the southwestern slopes of Mt. Dana. Given the slow-moving nature of the ice in Tioga Pass Valley (see "Profiler V.2 Take-Aways"), any ice coming off Mt. Dana's steep southwestern slopes would have greatly contributed to increasing the shear stress and strain rate of the ice in this region (shear stress is a product of ice density, gravity, ice thickness, and ice surface slope, all of which contribute exponentially to the strain rate.) The confluence of these two ice flows likely compressed and diverted the Tioga Pass Valley flow to the west, supporting Huber's revised hypothesis (Huber, 2001).

The second observation hints at the possibility of more undiscovered CPG erratics further west, closer to Tuolumne Meadows and CPG bedrock. Based on the conclusions derived from the first observation, the inference can be made that Kuna Crest and Mt. Dana contributed much of the ice flowing into Tuolumne Meadows. The high abundance of Kuna Crest Diorite and Dana Metamorphics found west of Mt. Dana further support this. Given that all three of the most distant CPG erratics were found at the base of moraines west of Mt. Dana, covered by the two aforementioned lithologies, this suggests that the ice flows from Mt. Dana and Kuna Crest outlasted any contributions of ice from Tioga Pass Valley. Any CPG erratics deposited further west are likely to have been buried under glacial sediment from the two flows which dominated this region.

PROFILER V.2 TAKE-AWAYS

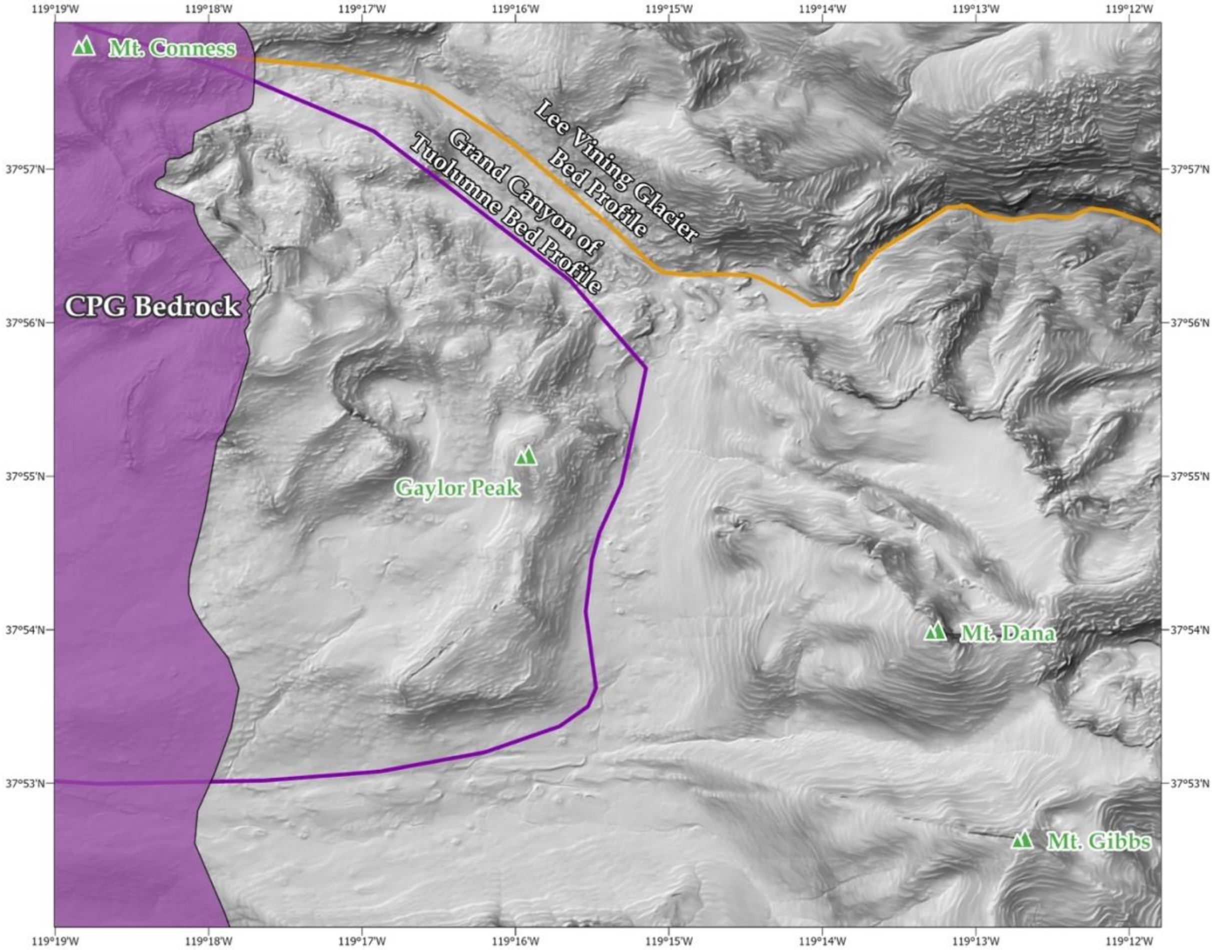

Figure 7 – The purple and orange lines depict the two bed profiles used for the two modeled flows. For the full .kml files, see appendix 2.

"Profiler V.2" models were incorporated into this project for two reasons:

(1) to understand the ice dynamics around Tioga Pass during peak LGM conditions;

(2) to provide insight into the presumed flow reversal, resulting in northward ice flow across Tioga Pass after peak LGM conditions.

To achieve the first goal, a flow model was constructed for the ice between the eastern cirque of Mt. Conness and a point on the Tuolumne River roughly seven kilometers west of the western edge of the Yosemite National Park boundary (this point corresponds with the end of an ice tongue). This flow was based on flow lines from Stock's plan-view map of ice coverage and flow directions in Yosemite at the peak of the LGM (Wahrhaftig et al. 2019). This flow was called the "Grand Canyon of Tuolumne Flow."

Once all four required parameters were input into the Excel™-based spreadsheet and the reconstructed ice surface model had been adjusted to meet the target elevations, the model provided a rough understanding of the basal shear stress values. The shear stress experienced at the base of a glacier is equal to:

$$\tau = \rho g h * \sin(\alpha)$$

where τ is the basal shear stress (Pa), ρ is the ice density (900 kg/m^3), g is gravity (9.81m/s^2), h is the ice thickness (m), and α is the ice surface slope. This indicates that the basal shear stress increases with some combination of increasing thickness and slope.

The model indicates that Tioga Pass Valley and the area just southwest of this valley were the sites of the lowest basal shear stress values for the entire 82-kilometer flow. Regions of Tioga Pass Valley reached basal shear stress values as low as 6 kPa, equivalent to less than 6% of the mean basal shear stress for the modeled ice flow. Another noteworthy measure, strain rate (s^{-1}) is a measure of the amount of a material's deformation with respect to time. While not all deformation in a glacier translates laterally, strain rate can but used to understand the flow rate of ice. Strain rate is a product of basal shear stress, and thus is directly proportional to the basal shear stress. This means that Tioga Pass was also the site of the slowest flowing ice for the modeled flow. These observations indicate that the ice responsible for transporting the CPG erratics exhibited nearly stagnant behavior upon reaching Tioga Pass Valley. As a result, this ice was subject to greater influence from any convergence with other ice flows, notably those from Gaylor Peak's northeast cirque, and Mt. Dana's north and southwest cirques. Given these values represent peak LGM conditions, subsequent retreat may have led to increasingly stagnant ice in Tioga Pass Valley.

To achieve the second goal of the "Profiler V.2" modelling, a second ice flow was modelled, this time from the east cirque of Mt. Conness to the base of Lee Vining Canyon, again using Stock's unpublished plan view map as a guide (*figure 1*) (Wahrhaftig et al. 2019). This model was to be compared to that for the Grand Canyon of Tuolumne flow. Given that glaciers, especially larger ice masses such as icefields, tend to flow in the downhill direction of the surface slope rather than the surface topography slope, the plan was to compare neighboring regions of the two flows to determine if, and when, a flow reversal may have occurred. After preparing the initial model, a simulated retreat was to be applied to both flows, executed by moving the terminuses up-slope by equal elevation changes until the ice surface slope indicated a downhill ice surface gradient from the Grand Canyon of Tuolumne flow toward the Lee Vining Canyon flow above Tioga Lake.

Initial peak LGM models indicated that the ice surface slope in question already exhibited the downhill ice surface slope expected to represent northward ice flow across Tioga Pass resulting in ice flow from Tioga Pass into Lee Vining Canyon (see *figure 8*). Given that the initial simulated conditions did not present an uphill ice surface slope from the Grand

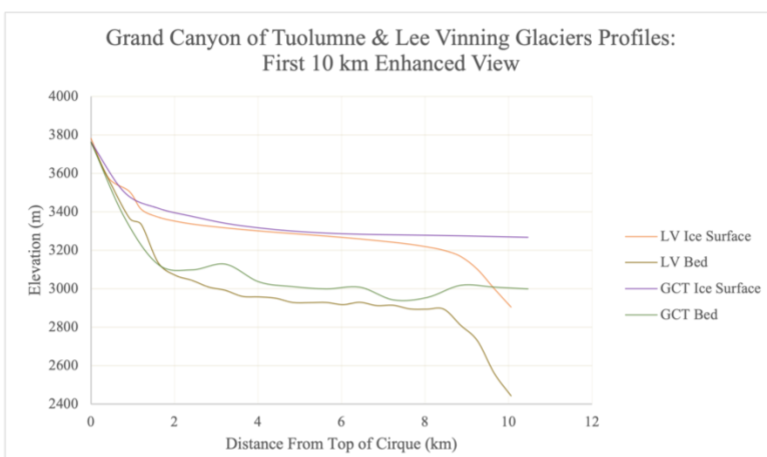

Figure 8 – Ice surface comparison for the Grand Canyon of Tuolumne and Lee Vining Canyon flows. The region of interest for determining ice surface slope between the two flows is between 3 and 5 km from the of the cirque.

Canyon of Tuolumne flow toward the Lee Vining Canyon flow, the regressions would not be able to indicate any flow reversal. This leads to three possible conclusions:

(1) the target elevations and ice surface level contours pulled from Stock's plan-view map are not sufficiently accurate or precise to be used for this model;
(2) other factors were at play during these initial conditions which diverted the flow from Mt. Conness toward Tioga Pass despite the downhill ice surface slope from Tioga Pass toward Lee Vining Canyon;
(3) the "Profiler V.2" model is not fit for modeling complex interactions between multiple glaciers.

Given that the ice surface level for the two flows in question differs by less than 30 meters, this first is a possibility. However, no uncertainty is provided in the plan-view map to be able to further evaluate this claim.

A likely factor is the flow from Mt. Dana's north cirque. This flow trended northwest from the cirque, down a glacial valley where it intersected with the flow from Mt. Conness' east cirque at the junction between Tioga Pass and Lee Vining Canyon. This flow directly opposed the flow direction of the Mt. Conness flow prior to any split into the valley or canyon. The opposing force produced by this ice flow may have been sufficient to induce significant internal ice deformation, producing more viscous ice which may have acted as a buffer between Tioga Pass and Lee Vining Canyon. This could have allowed for the Grand Canyon of Tuolumne flow to continue into Tioga Pass Valley at peak LGM conditions despite the downhill ice surface slope from Tioga Pass toward Lee Vining Canyon.

While the convergence of these two ice flows is apparent, the exact dynamics of the interplay of the two bodies was not mathematically evaluated in this study. The "Profiler V.2" spreadsheet is intended to be used to model the ice surface profile for a single ice flow exhibiting perfectly plastic behavior. It is not intended to be used to understand the interaction of two or more ice flows, nor any behavior that is non-plastic. As a result of the complex nature of flow interactions north of Tioga Pass, this model is prone to significant error. Evaluation of field evidence is likely to produce more conclusive evidence for any flow reversal.

INFERENCES FROM GLACIAL BEDFORMS AND STRIATIONS

There are three key regions where preserved glacial landforms indicate clear flow directions that are of interest to this study:

(1) the north cirque and glacial valley of Mt. Dana;
(2) the north cirques of Gaylor Peak;
(3) the southwestern glacial valley and lateral moraines of Mt. Dana.

As indicated in the previous section, the flow off the north slope of Mt. Dana is likely to have opposed the flows from the eastern cirque of Mt. Conness, inducing internal deformation and ultimately permitting ice at peak LGM conditions to branch into both Tioga Pass Valley and

Lee Vining Canyon. The valley produced by this glacier is preserved down to roughly 3250 meters above sea level. It is at this point that it converged with the flow from the eastern cirque of Mt. Conness (Wahrhaftig et al. 2019).

The north cirques of Gaylor Peak indicate clear flow to the northeast. Based on the plan-view map of ice coverage and flow direction (*figure 1*), these cirques are thought to have been covered by ice flowing south into Tioga Pass Valley at peak LGM conditions. The ice here is thought to have been rather thin (under 100 meters thick) by comparison to the rest of the surrounding flow (Wahrhaftig et al. 2019). As a result, this region was likely one of the first to become separated from the larger cohesive ice body moving south across Tioga Pass, allowing sections to develop their own flow directions. The presence of northeast facing cirques indicates this change. Further, roche-moutonnées northeast of these cirques indicate a northeastern flow from Gaylor peak into Lee Vining Canyon. Striations trending to the northeast in this area further support this.

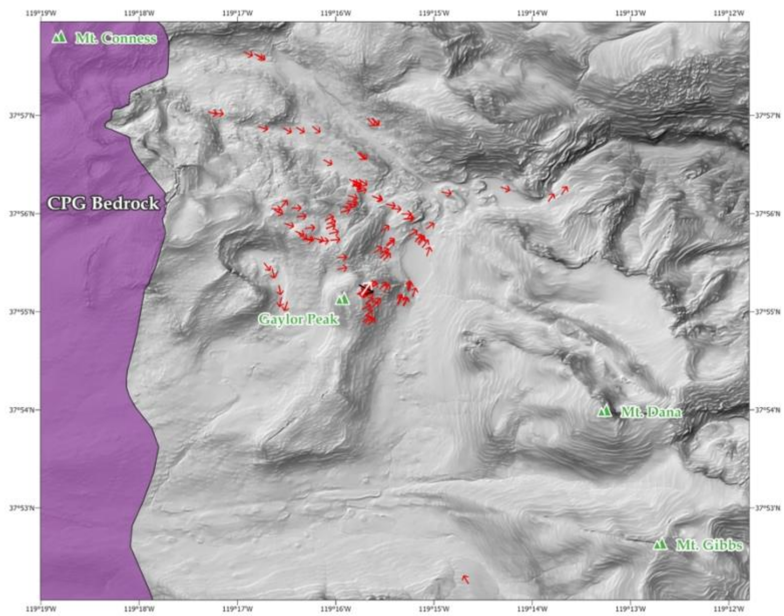

Figure 9 – Key striations (appendix 2, Wahrhaftig et al., 2019) are depicted in red, with a key set of cross-cutting striations depicted in black and white.

Sets of cross-cutting striations were found on the eastern edge of a cirque facing to the northeast on the north side of Gaylor Peak (Wahrhaftig et al., 2019). These striations indicate flow to the northeast, toward Lee Vining Canyon, and flow to the southeast, into Tioga Pass Valley. These striations support both the initial flow from the eastern cirque of Mt. Conness into Tioga Pass Valley, and later stage flow into Lee Vining Canyon which may have stranded the stagnant ice in Tioga Pass Valley. It is crucial to note that striations may be overprinted by any subsequent ice flow, thus striations often only preserve the most recent flow direction.

Finally, the preserved glacial valley and corresponding lateral moraines off the southwest slopes of Mt. Dana indicate clear flow into Tuolumne Meadows. These landforms have been previously interpreted to have diverted any flow from Kuna Crest or Tioga Pass into Tuolumne Meadows (Wahrhaftig et al., 2019).

CONCLUSION

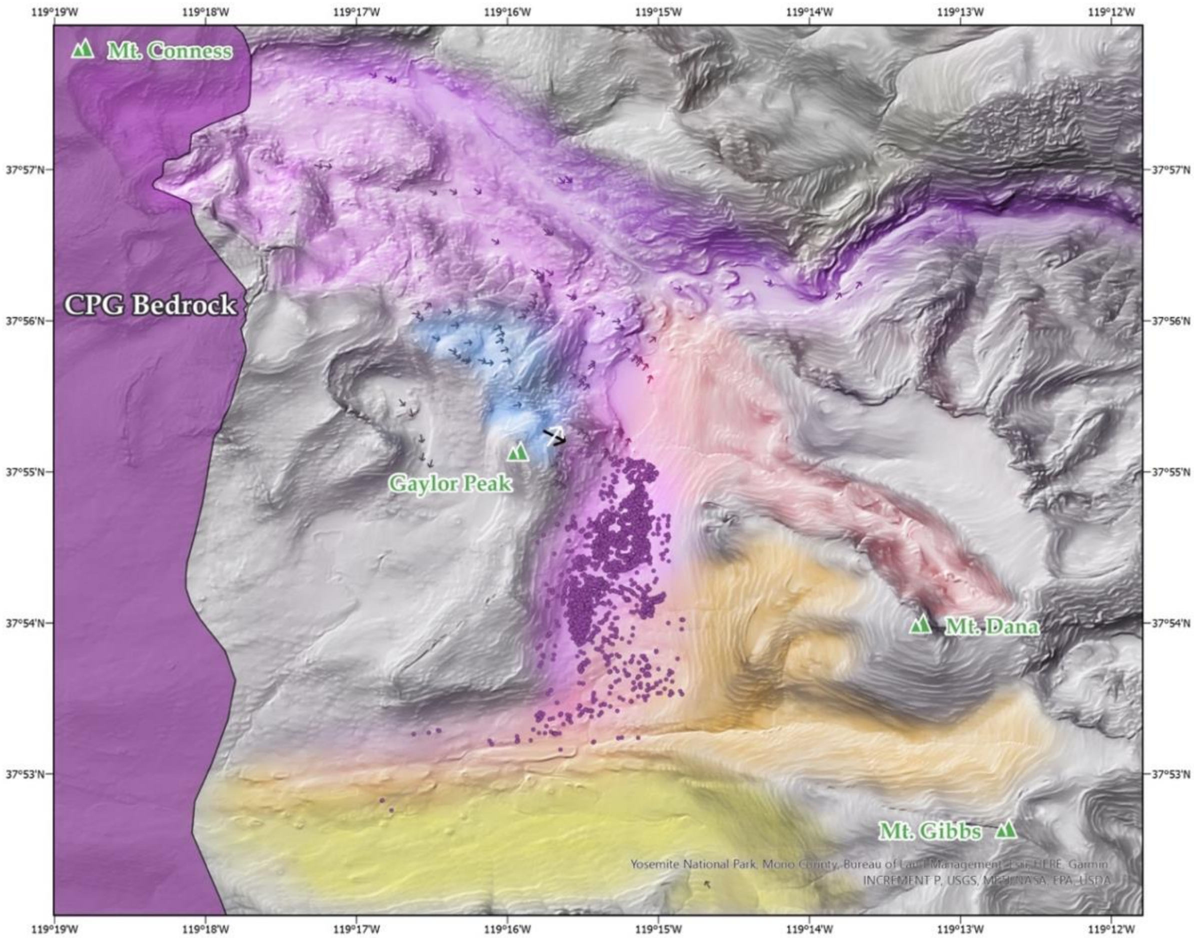

Figure 10 – This map depicts all key evidence in one frame. The purple points indicate all 2622 CPG erratics in the study area. The arrows north of Tioga Pass indicate key striations, including one set of cross-cutting striations marked in black and white. Finally, each color indicates a unique flow which is likely to have been influential to the ice covering Tioga Pass. The purple/pink marks the flows from the east cirque of Mt. Conness. The blue marks flow from Gaylor Peak post LGM conditions. The red marks the flow from the north of Mt. Dana which contributed to southward ice flow across Tioga Pass during peak LGM conditions, and northward ice flow down Lee Vining Canyon as ice thinned. The orange marks the flows from the southwest of Mt. Dana responsible for constricting and diverting ice from Tioga Pass west into Tuolumne Meadows. The yellow marks ice flow from Kuna Crest.

The 2622 CPG erratics mapped for this project serve to evaluate the distribution of Cathedral Peak Granite at Tioga Pass as a means for understanding the ice dynamics in this region during peak LGM conditions. This understanding was necessary to correct historical misrepresentations of ice flow direction across Tioga Pass. Based on the distribution of CPG erratics, which decreases with distance south of Tioga Pass, it can be concluded that ice flowed south across Tioga Pass, transporting these erratics from the eastern cirque of Mt. Conness to their current position. Upon reaching Tioga Pass, a “Profiler V.2” model used to construct ice surface elevation indicates that the ice in this region was slow moving and prone to stagnation.

Glacial landforms preserved southwest of Mt. Dana, along with a mapped boulder train of metamorphic rocks from Mt. Dana into Tuolumne Meadows, combine to discredit the possibility of ice flowing north across Tioga Pass from Tuolumne Meadows or Kuna Crest during peak LGM flow. Based on the preserved striations found north of Tioga Pass which indicate northeastern ice flow into Lee Vining Canyon, no late-stage glaciation resulted in ice flowing south into Tioga Pass Valley. Further, the presence of north facing cirques on Mt. Dana and Gaylor peak, along with their corresponding glacial bedforms, further support later-stage flow away from Tioga Pass Valley and into Lee Vining Canyon. These lines of evidence constrain any flow south into Tioga Pass Valley to peak LGM conditions. The cross-cutting striations found on the eastern edge of Gaylor Peak's north cirque provide a key to understanding the evolution of flow direction at Tioga Pass. Apart from these striations, all other striations around Tioga Pass indicate flow into Lee Vining Canyon. Given that striations are likely to be overprinted by any flow changes, they are considered to preserve the most recent dominant ice flow direction. While this indicates that ice flowed away from Tioga Pass after peak LGM conditions, the presence of the southeast trending striations in the set of cross-cutting striations indicates that some peak LGM flow conditions may have been preserved.

Based on the distribution of CPG erratics around Tioga Pass, the preserved glacial landforms to the north and south, the striations north of Tioga Pass, the cross-cutting striations north of Gaylor Peak, and a peak LGM conditions flow model for ice flow across Tioga Pass, there is strong evidence to support the standing hypothesis that peak LGM flow conditions saw ice flowing slowly south across Tioga Pass, followed by flow away from Tioga Pass and into Lee Vining Canyon following peak LGM conditions, leaving stagnant ice covering Tioga Pass Valley.

Some uncertainty remains regarding the exact ice dynamics north of the study area as the peak LGM conditions faded. To provide more clarity, future work could seek to map all glacial erratics in the region between Gaylor Peak, Tioga Lake, and the first hundred meters of Lee Vining Canyon, distinguishing between each unique lithology. Such work would require a high attention to detail as some lithologies appear similar (notably the full suite of Dana metamorphics and the metamorphic rocks of Gaylor Peak). A comprehensive map of all glacial erratics in this region would provide clearer insight into the role of each flow north of Tioga Pass after peak LGM conditions.

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